Parton sum rules and improved scaling variable

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Abstract

The effect from quark masses and transversal motion on the Gottfried, Bjorken, and Ellis-Jaffe sum rules is examined by using a quark-parton model of nucleon structure functions based on an improved scaling variable. Its use results in corrections to the Gottfried, Bjorken, and Ellis-Jaffe sum rules. We use the Brodsky-Huang-Lepage prescription of light-cone wavefunctions to estimate the size of the corrections. We constrain our choice of parameters by the roughly known higher twist corrections to the Bjorken sum rule and find that the resulting corrections to the Gottfried and Ellis-Jaffe sum rules are relevant, though not large enough to explain the observed sum rule violations.

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Parton sum rules provide information on the quark distributions in nucleons and thus allow for sensitive tests of QCD. Recently, the Gottfried sum rule (GSR) [1] violation reported by the New Muon Collaboration (NMC) [2] has inspired a number of discussions on flavor dependence of sea distributions in the nucleons [3]. For polarized structure functions the violation of the Ellis-Jaffe sum rule (EJSR) [4] observed at CERN [5, 6] and SLAC [7, 8] has triggered extensive investigations [9]. In this letter we examine the effect of quark masses and transversal motion on structure functions using an improved quark-parton model [10, 12] formulated in the framework of light-cone quantum field theory [11]. It will be shown that the kinematical corrections to the Gottfried, Bjorken, and Ellis-Jaffe sum rules are non-trivial.

We first examine the Gottfried sum rule. According to the quark-parton model, the nucleon structure functions $F_2^N(\nu, Q^2)$ scale in the Bjorken scaling variable $x_B = Q^2/2M\nu$ in the Bjorken limit $\nu \to \infty$, $Q^2 \to \infty$ with $Q^2/2M\nu$ fixed, i.e.,

$$F_2^N(\nu, Q^2) = F_2^N(x_B) = \sum_i e_i^2 x_B [q_i^N(x_B) + \overline{q}_i^N(x_B)], \qquad (1)$$

where $q_i(x_B)$ ($\overline{q}_i(x_B)$) is the quark (anti-quark) momentum distribution function, e_i is the charge of of a quark of flavor i, and N represents the proton p or neutron n. The QCD corrections to flavor number conservation $\int_0^1 [u^p(x_B) - \overline{u}^p(x_B)] \, dx_B = 2$ etc. are small [13]. Thus the Gottfried sum

can be expressed as

$$S_G = \int_0^1 [F_2^p(x_B) - F_2^n(x_B)] \, \mathrm{d}x_B/x_B \; = \frac{1}{3} + \int_0^1 \sum_i [2\overline{q}_i^p(x_B) - 2\overline{q}_i^n(x_B)] \, \mathrm{d}x_B.$$

(2)

Under the assumptions of isospin symmetry between proton and neutron, and flavor symmetry in the sea, one arrives at the Gottfried sum rule (GSR), $S_G = 1/3$. In the NMC experiment, the value of S_G was determined from the ratio F_2^d/F_2^p in the kinematic range of $x = 0.004 - 0.8$ for $Q^2 = 4 \text{ GeV}^2$. Assuming a smooth extrapolation of the data for F_2^n/F_2^p from $x = 0.8$ to $x = 1$, adopting a Regge behavior ax^b for $F_2^p - F_2^n$ (a flavor nonsinglet quantity) in the region $x = 0.004 - 0.15$ and then extrapolating it to $x = 0$, the NMC reported

$$S_G = 0.235 \pm 0.026,$$

(3)

which is significantly smaller than the simple quark-parton-model result of 1/3. Several different explanations for the origin of the GSR violation have been proposed, such as flavor asymmetry of the nucleon sea [14, 15], isospin symmetry breaking between the proton and the neutron [16], non-Regge behaviors at small x [17], and nuclear effects like mesonic exchanges in the deuteron [18] and nuclear bindings [19]. Recently, it has been concluded in [20] by using an improved scaling variable that the kinematic corrections may account for a significant part of the GSR violation. It is the last proposition that we want to reanalyse.

Several years ago, an improved quark-parton model for nucleon structure functions was developed [10] based on light-cone quantum field theory[11]. The resulting nucleon structure functions have the form

$$F_2^N(\nu, Q^2) = \sum_i e_i^2 x_p \mathcal{K}[q_i^N(x_p) + \overline{q}_i^N(x_p)], \tag{4}$$

where

$$\mathcal{K} = q^-/k'^- = 2M\nu x_p/(m^2 + (\mathbf{k}_\perp + \mathbf{q}_\perp)^2), \tag{5}$$

$$x_p = (A - B)/2(M^2 + 2M\nu) \tag{6}$$

with

$$A = M^2 + 2M\nu + (\mathbf{k}_\perp + \mathbf{q}_\perp)^2 + m^2 - \mathbf{k}_\perp^2 - \lambda^2;$$
$$B = (A^2 - 4[(\mathbf{k}_\perp + \mathbf{q}_\perp)^2 + m^2](M^2 + 2M\nu))^{1/2}, \tag{7}$$

m and λ are the masses of the struck quark and the spectator treated as a single particle, $\mathbf{k}_\perp$ is the transversal quark momentum, $\mathbf{q}_\perp$ is the transversal component of the lepton momentum transfer specified by $q_\nu = (q^+, q^-, \mathbf{q}_\perp) = (0, 2\nu, \mathbf{q}_\perp)$ with $q^2 = -Q^2$, and x_p is the improved scaling variable. It gives power-law type corrections to Bjorken scaling violation which might be present in some experimental data [10]. Let us note that x_p reduces to the Bloom-Gilman variable, the Weizmann variable, and the Nachtmann variable in appropriate approximations. The kinematical factor $\mathcal{K} = q^-/k'^-$ is almost equal to unity in the whole Q^2 region, even when Q^2 is small. Unfortunately, a good use of the improved scaling variable requires more detailed information on the nucleon wave functions than

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presently available. In this work, we simply adopt the Brodsky-Huang-Lepage (BHL) prescription [11] for the momentum space wave function in a light-cone SU(6) quark-spectator model for deep-inelastic scattering [21, 22] to analyse the effect due to finite quark masses and transversal motion in the Gottfried sum.

In the Bjorken limit the factor $\mathcal{K}$ reduces to unity and the improved scaling variable x_p becomes identical to the Bjorken variable (Eq. (4) reduces to Eq. (1)). However, at finite Q^2 the correct condition for flavor number conservation is $\int_0^1 [u^p(x_p) - \overline{u}^p(x_p)]\, \mathrm{d}x_p = 2$ etc., and Eq. (2) does not hold exactly. Under the assumption of a flavor and isospin symmetric sea in the nucleons, we obtain

$$S_G = \int_0^1 (F_2^p(x_B) - F_2^n(x_B))\, \mathrm{d}x_B/x_B = \frac{1}{3} \int_0^1 x_p \mathcal{K}[u_v(x_p) - d_v(x_p)]\, \mathrm{d}x_B/x_B.$$

$$(8)$$

The valence quark distributions $u_v(x)$ and $d_v(x)$ in the SU(6) quark-spectator model are expressed by

$$u_v(x) = \tfrac{1}{2}a_S(x) + \tfrac{1}{6}a_V(x);$$
$$d_v(x) = \tfrac{1}{3}a_V(x),$$

$$(9)$$

where $a_D(x)$ ($D = S$ or V for scalar or vector spectators) denotes the amplitude for the quark q is scattered while the spectator is in the diquark state D and is normalized such that $\int_0^1 \mathrm{d}x a_D(x) = 3$ [21, 22]. Thus we can

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write

$$a_D(x_p) \propto \int [\mathrm{d}x][\mathrm{d}^2\mathbf{k}_\perp]|\varphi_D(x, \mathbf{k}_\perp)|^2 \delta(x - x_p), \tag{10}$$

where $\varphi_D(x, \mathbf{k}_\perp)$ is the BHL light-cone momentum space wave function of the quark-spectator

$$\varphi_D(x, \mathbf{k}_\perp) = A_D exp\{-\frac{1}{8\beta_D^2}[\frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1 - x}]\}. \tag{11}$$

Here $\mathbf{k}_\perp$ is the internal quark transversal momentum, m_q and m_D are the masses for the quark q and spectator D, and β_D is the harmonic oscillator scale parameter. Combining Eqs. (8) and (9), we have

$$S_G = \frac{1}{3}\int_0^1 x_p \mathcal{K}[\frac{1}{2}a_S(x_p) - \frac{1}{6}a_V(x_p)] \, \mathrm{d}x_B/x_B = \frac{1}{6} < a_S > - \frac{1}{18} < a_V >, \tag{12}$$

where

$$< a_D > = \int_0^1 [\mathrm{d}x_B][\mathrm{d}^2\mathbf{k}_\perp]\frac{x_p}{x_B}\mathcal{K} \, a_D(x_p). \tag{13}$$

The values of the parameters β_D, m_q and m_D can be adjusted by fitting the hadron properties such as the electromagnetic form factors, the mean charge radiuses, and the weak decay constants etc. in the relativistic light-cone quark model [23]. We used various sets of parameters allowed by these constraints and calculated the resulting corrections to Bjorken and Ellis-Jaffe sum rules for various values of $Q^2 \gg 1$ GeV^2. As both mass and transverse momentum corrections are higher twist effects the resulting Q^2 dependence can be fitted for large Q^2 by a term c/Q^2. Sum rule calculations suggest

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$-0.02 \leq c(B) \leq 0.03$ GeV^2 and $-0.04 \leq c(EJ) \leq 0.01$ GeV^2 [24]. In view of principal uncertainties in the sum rule approach these numbers are chosen very conservatively and should be interpreted as constraints. For many otherwise acceptable parametrizations our model results in much larger values for c. We used therefore the sum rule values to restrict the parameter range of our model much tighter. And for this restricted parameter range the resulting corrections to the polarized sum rules were calculated for the experimentally relevant small values of Q^2 and the corrections to the Gottfried sum rule were estimated. All corrections turned out to be noticeable but not large and the remaining allowed parameter variations have little effect. We shall present results as example for $m_q = 220$ MeV, $\beta_S = \beta_V = 220$ MeV, $m_S = 400$ MeV, and $m_V = 600$ MeV (set I). (The masses of the scalar and vector spectators should be different taking into account the spin force from color magnetism or alternatively from instantons [25].) To explore the maximal range of parameters we shall also allow for SU(6) asymmetric wavefunctions by choosing the parameters $m_q = 220$ MeV, $\beta_S = 280$ MeV, $\beta_V = 180$ MeV, $m_S = 400$ MeV, and $m_V = 600$ MeV (set II). This fit leads to higher twist corrections which are rather too large to be acceptable, namely $c(B) \simeq c(EJ) \simeq -0.05$. Still we include it for comparison.

With the above parameters we find for set I:

$S_G = 0.304$ for $Q^2 = 3$ GeV^2 and $S_G = 0.324$ for $Q^2 = 10$ GeV^2

implying that the correction to Gottfried sum rule is small. For the 'exotic'

set II we get:

$S_G = 0.282$ for $Q^2 = 3$ GeV^2 and $S_G = 0.316$ for $Q^2 = 10$ GeV^2

showing that even with extreme assumptions the kinematic corrections can account at most for part of the observed sum rule violation.

There has been a similar work by Sawicki and Vary [20] on off-shell corrections to the parton model. They arrived at the conclusion that the kinematic corrections may account for a substantial part of the GSR violation. There are some important differences between their and our calculation apart from the fact that we use the known bounds on higher twist contributions to constrain the range of allowed parameters. First, they assumed the conservation of four-momentum at the photon-parton vertex and used $\tilde{x} = x_B(1 + \frac{m^2 + 2\mathbf{k}_\perp \cdot \mathbf{q}_\perp - k^2}{Q^2})$ as the revised scaling variable. However, in light-cone quantum field theory [11] "energy" is not conserved at the photon-parton vertex but only between the initial and final states. The scaling variable x_p we used is therefore different from $\tilde{x}$. Second, in the NMC experiment, the Gottfried sum was obtained by using $S_G = \int_0^1 (F_2^p(x_B) - F_2^n(x_B))\ \mathrm{d}x_B/x_B$, where the measured data $F_2^N(x_B)$ were divided by the Bjorken scaling variable x_B rather than the revised scaling variable x_p or $\tilde{x}$ in the integration over x_B. The use of the improved scaling variables x_p or $\tilde{x}$ exhibits a shift of the actual parton distributions towards higher values of x_p or $\tilde{x}$. While the contribution due to the improved scaling variable x_p tends to reduce the Gottfried sum S_G this effect

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is partially canceled by the factor $1/x_B$ (rather than $1/x_p$). This aspect was ignored in [20]. Our kinematic factor $\mathcal{K}$ is also larger than the factor $x_B/\tilde{x}$ in [20] and finally the size of our corrections is constrained by fitting the higher twist contributions to Bjorken sum rule.

We now turn our attention to the Ellis-Jaffe sum rule. Following Ref. [10], we obtain for the antisymmetric part of the hadron scattering tensor $W^A_{\mu\nu}$ in light-cone quantum field theory [11]

$$W^A_{\mu\nu} = \sum_q \int \frac{\mathrm{d}^2\mathbf{k}_\perp \mathrm{d}k^+}{16\pi^3 k^+} \frac{\rho_q(\underline{k})}{x} w^A_{\mu\nu}(k, k'), \tag{14}$$

$$w^A_{\mu\nu}(k, k') = i\epsilon_{\mu\nu\lambda\sigma} e_q^2 q^\lambda s^\sigma \delta(p^- + q^- - k'^- - \sum_{i=2}^n k_i^-)/k'^+, \tag{15}$$

where $\rho_q(\underline{k})$ is the distribution function for the quark q in the nucleon bound state as a function of the light-cone three-momentum ($\underline{k} = (k^+, \mathbf{k}_\perp)$). For g_1 this implies

$$g_1(\nu, Q^2)S^\sigma = \sum_q e_q^2 p \cdot q \int \frac{\mathrm{d}^2\mathbf{k}_\perp \mathrm{d}k^+}{16\pi^3 k^+} \frac{\rho_q(\underline{k})}{x} s^\sigma \delta(p^- + q^- - k'^- - \sum_{i=2}^n k_i^-)/k'^+. \tag{16}$$

Calculating the $+$ component of Eq. (16) and treating the δ-function as in Ref. [10], we obtain ($\Delta q(x) = q^\uparrow(x) - q^\downarrow(x)$)

$$g_1(\nu, Q^2) = \frac{1}{2} \sum_q e_q^2 \int_0^1 \mathcal{K}\Delta q(x)\delta(x - x_p) \, \mathrm{d}x, \tag{17}$$

with $q^\uparrow(x)$ ($q^\downarrow(x)$) being the probability of finding a quark of flavor q with light-cone helicity parallel (antiparallel) to the target spin [12].

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The use of the improved scaling variable can also have a non-trivial consequence on the Ellis-Jaffe sum rule violation reported by several experimental groups. For the sake of simplicity, we consider only valence quark contributions to $g_1^N(\nu, Q^2)$ and neglect contributions from the sea. In the SU(6) quark-spectator model [21, 22] the quark helicity distributions for the valence quarks read

$$\Delta u_v(x, \mathbf{k}_\perp) = u_v^\uparrow(x, \mathbf{k}_\perp) - u_v^\downarrow(x, \mathbf{k}_\perp)$$

$$= -\tfrac{1}{18} a_V(x, \mathbf{k}_\perp) W_V(x, \mathbf{k}_\perp) + \tfrac{1}{2} a_S(x, \mathbf{k}_\perp) W_S(x, \mathbf{k}_\perp); \qquad (18)$$

$$\Delta d_v(x, \mathbf{k}_\perp) = d_v^\uparrow(x, \mathbf{k}_\perp) - d_v^\downarrow(x, \mathbf{k}_\perp) = -\tfrac{1}{9} a_V(x, \mathbf{k}_\perp) W_V(x, \mathbf{k}_\perp),$$

where $W_D(x, \mathbf{k}_\perp)$ is the correction factor due the Wigner rotation effect [12]

$$W_D(x, \mathbf{k}_\perp) = \frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} \qquad (19)$$

with $k^+ = x\mathcal{M}$ and $\mathcal{M} = \frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}$. Thus we can write the Ellis-Jaffe and Bjorken sums as

$$S_{EJ}^p = \tfrac{1}{9} < W_S > - \tfrac{1}{54} < W_V >;$$
$$S_{EJ}^n = \tfrac{1}{36} < W_S > - \tfrac{1}{36} < W_V >, \qquad (20)$$

and

$$S_B = S_{EJ}^p - S_{EJ}^n = \tfrac{1}{12} < W_S > + \tfrac{1}{108} < W_V >, \qquad (21)$$

where

$$< W_D > = \int_0^1 [\mathrm{d}x_B][\mathrm{d}^2 \mathbf{k}_\perp] \mathcal{K} \, a_D(x_p) W_D(x_p). \qquad (22)$$

We calculate the Ellis-Jaffe and Bjorken sums with the above adopted parameters and find for set I:

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$S_{EJ}^p = 0.210$, $S_{EJ}^n = -0.001$, and $S_B = 0.209$ at $Q^2 = 3$ GeV^2 and $S_{EJ}^p = 0.214$, $S_{EJ}^n = -0.0003$, and $S_B = 0.214$ at $Q^2 = 10$ GeV^2,

which is far off the experimental values $S_B(E143) = 0.163 \pm 0.010 \pm 0.016$ and $S_B(SMC) = 0.199 \pm 0.038$. For set II one gets closer to the data:

$S_{EJ}^p = 0.174$, $S_{EJ}^n = -0.012$, and $S_B = 0.186$ at $Q^2 = 3$ GeV^2 and $S_{EJ}^p = 0.186$, $S_{EJ}^n = -0.011$, and $S_B = 0.214$ at $Q^2 = 10$ GeV^2,

which is in good agreement with the experimental values of the Bjorken sum but still far off the Ellis-Jaffe sums: $S_{EJ}^p(E143) = 0.127 \pm 0.004 \pm 0.010$, $S_{EJ}^n(E143) = -0.037 \pm 0.008 \pm 0.011$ at $< Q^2 > = 3$ GeV^2 and $S_{EJ}^p(SMC) = 0.136 \pm 0.011 \pm 0.011$, $S_{EJ}^n(SMC) = -0.063 \pm 0.024 \pm 0.013$ at $< Q^2 > = 10$ GeV^2. Let us note for comparison that the naive Ellis-Jaffe sum rule would result in $S_{EJ}^p(SMC) = 0.171 \pm 0.006$, see ref. [6]. Obviously the sea quarks, which are missing in the BHL wave function, are important for the Ellis-Jaffe sum rule. Work on an extension of the BHL wave functions to include intrinsic sea quarks is on the way [27] and it will be very interesting to use the resulting wave functions to calculate the Ellis-Jaffe sum rule. This will, however, still require substantial work.

Fig. 1 shows the spin asymmetries $A_1^p(x) = 2xg_1^p(x)/F_2^p(x)$ and $A_1^n(x) = 2xg_1^n(x)/F_2^n(x)$ resulting for the parameters of sets I and II. It is obvious that both sets do not fit the data well. The discrepancies occure mainly for small x where one would expect the sea quark contribution to be sizeable.

In summary, we analysed the Gottfried, Bjorken, and Ellis-Jaffe sums

in an improved quark-parton model description of nucleon structure functions. It is found that the effects from finite quark masses and transversal motion are noticeable but not large, in contrast to claims in the literature. Furthermore we found that a constraint derived from the size of the higher twist corrections to the Bjorken and Ellis-Jaffe sum rules substantially reduce the allowed parameter range, which is important for all applications of this model. The same observation is probably true for other model wavefunctions. This fact high-lights the far reaching importance of a precise determination of higher twist effects. The observed discrepancies for the Gottfried and Ellis-Jaffe sum rules are reduced but not explained by our kinematic corrections. A drawback of the specific BHL wave functions we used is their lack of an intrinsic sea quark distribution. We are currently working on an improvement of these wave functions [27].

ACKNOWLEDGMENTS

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Figure Captions

Fig. 1. The spin asymmetries $A_1^p(x)$ and $A_1^n(x)$ calculated in the light-cone SU(6) quark-spectator model [22] with the Martin-Roberts-Stirling (S_0') parametrizations of unpolarized quark distributions [26]. The data are EMC($\triangle$), SMC($\square$), and E143($\bigcirc$) for $A_1^p(x)$ and E142($\diamond$) for $A_1^n(x)$ [5, 6, 7, 8]. The solid and dashed curves are the results for parameter set I and II for $A_1^p(x)$ and $A_1^n(x)$ calculated at $Q^2 = 5$ GeV^2.
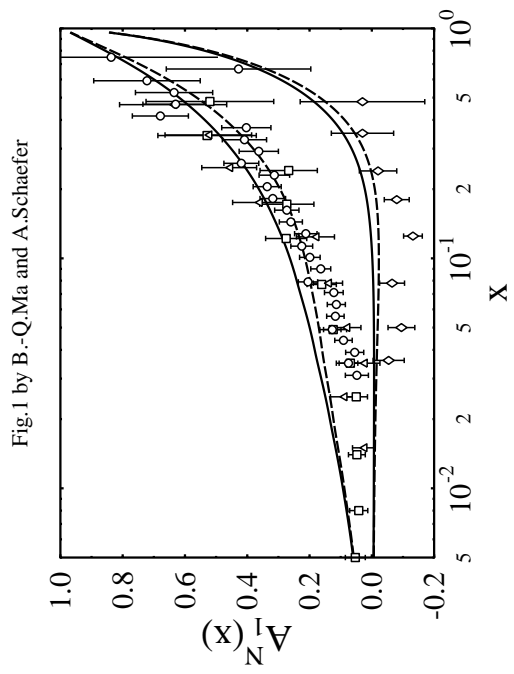
Fig.1 by B.-Q.Ma and A.Schaefer